UCRL-JC-132783
Preprint

On the Nature of the Optimal Control Problem at Leaking Underground Fuel Tank Sites

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This paper was prepared for submittal to
Australian Agricultural & Resource Economics Society, Inc. 43rd Annual Conference
Christchurch, New Zealand
January 20-22, 1999

December 1, 1998

Lawrence Livermore National Laboratory

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Contributed Paper
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Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

I. Introduction

As of 1995, the state of California was faced with over 21,000 identified sites at which fuel hydrocarbons (FHCs) had leaked from underground storage tanks (USTs) into soils and groundwater. With an overall fiscal effect on the California economy of about $3 billion, the resources required to manage the potential risks from these leaking underground fuel tank (LUFT) sites are significant. With the projected funding at the state level projected to be only $1.5 billion, a significant shortfall is anticipated (Rice et al., 1995).

The fundamental problem facing regulators is dynamic in nature. A stock of hazardous materials is released to the environment. This stock of material results in social damages, either by increasing the potential for human health or ecological risk, or by limiting land or water uses. The stock level declines over time due to natural biodegradation and active remediation efforts. As effort is expended to reduce stock levels, the social damages decline.

The primary guidance document used by regulators to manage LUFT sites is the *Leaking Underground Fuel Tank Field Manual (LUFT Field Manual)*. developed by the California Department of Health Services (DHS) and the State Water Resources Control Board (SWRCB). The *LUFT Field Manual* procedures were intended not only to avoid unwarranted expense, analysis or delays but also to ensure that site characterization is adequate to identify the extent of, and designing an appropriate response to, FHC soil contamination problems (Rice et al., 1995). The *Field Manual* procedures usually specify the projected time for cleanup and the acceptable residual contaminant level, which, in most cases, is the maximum contaminant levels (MCLs) for drinking water.

Recently, there has been recognition in California that the requirement to clean up groundwater to MCLs does not permit regulators to balance considerations of cost and technical feasibility against the protection of human health and the beneficial use of land and water resources (Rice et al., 1995). In addition, the *LUFT Field Manual* does not recognize or consider the capacity of the environment to degrade FHCs naturally through microbial action. Complaints have also been voiced that cleanup requirements are not consistently applied statewide. Moreover, no systematic framework exists to close many difficult cases where residual contamination above MCLs is technically and economically infeasible to remove.

A risk-based corrective action framework developed by the American Society of Testing and Materials has recently been proposed as the process by which LUFT cleanup can be systematically and consistently addressed (Rice et al., 1995). However, Section 13241 of the California Water Code also lists factors that the state's Regional Water Quality Control Boards (RWQCBs) should consider in setting water quality objectives. Factors listed in the Water Code include “economic considerations,” but what these considerations are or how they may affect the optimal cleanup at a LUFT site is not defined in the Water Code. A systematic method of assessing the costs and the benefits of groundwater cleanup is needed for consistent statewide application of cleanup requirements.

In a paper, “Optimal Cleanup of Hazardous Wastes,” appearing in the *International Economic Review*, Caputo and Wilen (1995) developed a dynamic model of waste accumulation in the environment with the objective of minimizing the discounted sum of cleanup and damage costs at Superfund sites. Their model explicitly recognized nature’s pollution degradation capacity and examines how fast and how complete cleanup should be. The model allows cleanup goals and end dates to be free, in order to identify optimal cleanup paths. Because resources available for LUFT-site cleanup are also limited, a similar model for optimal LUFT-site cleanup would be a valuable tool for consistent and efficient action by California regulators.

This paper examines the nature of the optimal control problem at California’s LUFT sites. The effectiveness of the model developed by Caputo and Wilen depends on assumptions regarding the nature of the functions of social damage and cleanup cost as well as the natural rate of decay of FHC waste in the environment. At LUFT sites, the nature of these functions are determined by the regulatory framework of cleanup, the effectiveness of available cleanup technologies, the transport of FHCs in soils and groundwater, assumptions regarding future land and groundwater use, and the microbial biodegradation capacity. By examining each of these in turn, we can evaluate whether the model proposed by Caputo and Wilen can be used to identify optimal cleanup paths at LUFT sites or whether another model may be more appropriate.

Each section of this paper evaluates a part of the optimal control problem at LUFT sites. Section II describes the constraints imposed by the regulatory framework for cleanup. Section III describes the movement of FHCs in the environment following a release from an underground tank. Section IV reviews the current state of cleanup technology. Section V discusses the social damages that result from a FHC release, particularly risks to human health and the environment, and the limitations imposed on land and water use. Section VI discusses the natural capacity of the environment to degrade FHCs. Based on the discussions in previous sections, Section VII evaluates the assumptions of the Caputo and Wilen model and poses a formulation of the optimal control problem that could be solved to yield the optimal cleanup path at many LUFT sites. Section VIII presents conclusions and identifies areas where additional research is needed.

II. Regulatory Framework

California regulates USTs through a framework of laws; regulations; and state, regional, and local policies. The California Water Code is the law from which the regulations and policies are derived. The Porter-Cologne Water Quality Control Act, Chapter 1, Division 7, of the California Water Code, stipulates to state and regional water boards that "those activities and factors [that] may affect the quality of the waters of the state shall be regulated to attain the highest water quality which is reasonable; considering all demands being made and to be made on those waters and the total values involved, beneficial and detrimental, economic and social, tangible and intangible. . . ." The SWRCB resolutions are policies used to implement the California Water Code. SWRCB resolutions are prepared through a public hearing process and consideration of the current extent of knowledge and experience.

LUFT regulatory oversight is conducted by the state's nine RWQCBs and 20 local oversight program regulatory agencies (19 counties and one water district) under contract with the SWRCB. These agencies are responsible for determining when cleanup requirements have been met and when LUFT cases can be closed. Because different regions have a range of hydrogeologic settings and water management practices and uses, the SWRCB and RWQCBs are required by law to manage the state's water resources through a policy that considers "factors of precipitation, topography, population, recreation, agriculture, industry and economic development [that] vary from region to region within the state, and that the statewide program can be most effectively administered regionally, within a framework of state coordination and policy" (California Water Code, Chapter 1, Section 13000, Division 7).

The RWQCBs develop Regional Basin Plans to establish the present and probable beneficial uses of water within their regions. These plans are subject to SWRCB policies during the formulation of water quality objectives and beneficial uses. According to Section 13241 of the California Water Code, the factors that the RWQCBs should consider in setting water quality objectives "shall include, but not necessarily be limited to, all of the following:

a) past, present, and probable future beneficial uses of water,
b) environmental characteristics of the hydrographic unit under consideration, including the quality of water available thereto,
c) water quality conditions that could reasonably be achieved through coordinated control of all factors which affect water quality in the area,
d) economic considerations
e) the need for developing housing in the region, and
f) the need to develop and use recycled water."

In 1983, California began to regulate USTs containing FHCs (such as gasoline, jet fuel, diesel fuel, and fuel oils) in response to a perceived threat that these tanks posed to the state's groundwater resources. A 1984 survey showed that there were approximately 200,000 USTs within the state.

The SWRCB promulgated California Underground Storage Tank Regulations in 1985. According to these regulations, a responsible party is required to perform soil and groundwater investigations if any of the following circumstances apply:

1. There is evidence that surface water or groundwater has been or may be affected by the unauthorized release.
2. Free product is found at the site where the unauthorized release occurred or in the surrounding area.
3. There is evidence that contaminated soils are or may be in contact with surface water or groundwater.
4. The regulatory agency requests an investigation, based on the actual or potential effects of contaminated soil or groundwater on nearby surface or groundwater resources or based on the increased risk of fire or explosion.

The California *LUFT Field Manual* was prepared in 1985 and revised in 1989 to address the regulatory problem of a growing number of contaminated fuel sites in the state. The document was created by a 38-member LUFT Task Force comprised of SWRCB and DHS staff. The intended users include regulators and environmental engineering consulting firms that assist responsible parties in cleanup.

Numerical groundwater goals are specified in California laws and regulations. If the probable beneficial use, as specified within a RWQCB Basin Plan, is municipal (MUN), the cleanup goals are restricted to MCLs, or background. SWRCB Resolution 88-63, known as the Sources of Drinking Water Policy, requires a broad designation of MUN to groundwater. Site-specific cleanup standards are not allowed within California's regulatory framework. Basin Plans also specify an anticipated time frame for beneficial use.

In the context of the 1995 Caputo and Wilen model, the regulatory framework imposes constraints on the optimal cleanup problem. The broad application of the MUN designation to groundwater results in a strict requirement to clean up groundwater to MCLs and can be interpreted as fixing the ending stock level. By establishing an anticipated beneficial-use time, the terminal date of the problem is also specified. Thus, under this kind of regulatory framework, the endpoints of the optimal cleanup problem are fixed.

It should be noted that in cases where: 1) there are no risks to human health or the environment, 2) passive bioremediation is occurring at a rate sufficient to reach MCLs prior to the anticipated beneficial use, and 3) institutional controls exist to prevent exposure during the passive remediation period, regulators may issue a no-further-action letter to the responsible parties (Rice et al., 1998). In these cases, regulators can implicitly incorporate risk-based cleanup criteria into their decisions. The institutional controls can take the form of restrictions on future use that are made part of the affected property deed, i.e., deed restrictions. This is generally not a viable option to regulators, however, because the time necessary to reach MCLs through active remediation—let alone passive bioremediation—generally greatly exceeds the anticipated time of beneficial use.

III. Fate and Transport of FHCs in the Environment

At LUFT sites, spilled or leaked FHCs percolate downward from the release point under the force of gravity. During this downward movement, some of the FHCs sorb onto soil particles or become lodged in pore spaces, others volatilize and migrate through air-filled pore spaces, and still others continue downward migration. If a low permeability zone is encountered, the FHCs tend to spread laterally. FHCs follow the path of least resistance, having a strong propensity to migrate along rock fractures, sand lenses, zones of high water content, clay layers, or man-made features, such as leach fields and dry wells.

The downward migration continues to the vadose zone where FHCs are distributed through lateral spreading. As FHCs build up, sufficient "head" is developed, and the more soluble components tend to dissolve into the capillary fringe of the water table. The dissolved FHCs then move through the capillary fringe into the groundwater. As groundwater itself moves, the FHC plume spreads. In both the unsaturated zone and in groundwater, some of the FHCs sorb onto soil particles, and others volatilize into unsaturated pore space above the water table. Absent any biodegradation process, and assuming that the FHCs source is inactive, volatilization and sorption by themselves will ultimately limit the spatial extent of the plume. The additional retardation of plume spread by bioremediation is discussed below.

In 1995, the Lawrence Livermore National Laboratory, in conjunction with the University of California at Berkeley, Davis, Santa Barbara, and Los Angeles conducted a review of the regulatory and cleanup process currently applied to LUFT sites in California (Rice et al., 1995). In California, the LUFT team evaluated 271 well-characterized LUFT sites with data covering a 10-year period. In addition, the University of Texas at Austin also evaluated historical records of underground tank sites (Mace et al., 1997). From these studies, the following tendencies emerged:

- In general, the team found that plume lengths change slowly and tend to stabilize at relatively short distances from the FHC release point. Average plume lengths rarely exceeded 250 feet.

- Nearly half of these sites had shallow groundwater with depths of less than 15 feet. Most sites have multiple soil layers, and clay was widespread. Plumes at sites with shallow groundwater almost never showed increasing lengths.

- After a plume was established, plume average concentrations tended to decrease much more rapidly than plume lengths. This is due to the tendency of FHCs to sorb onto soil particles. Of the 271 sites, 89 (or 33%)

had no significant trends in plume concentrations, and 161 (or 59%) had decreasing plume concentration trends.

- Of the estimated 1.3 billion acre-feet of basin storage capacity, only approximately 7,060 acre-feet (or 0.0005%) may have been impacted above a benzene concentration of 1 ppb.

- Out of 12,151 public supply water wells tested statewide, 48 (or 0.4%) were reported to have measurable benzene concentrations. Out of 28,051 LUFT sites, only 136 (or 0.5%) have reportedly affected drinking water wells.

The finding that most plumes are stable within a short distance of the release point is significant. Based on these findings, the LUFT team concluded that FHCs have limited impacts on human health, the environment, and California’s groundwater resources.

IV. Effectiveness of Available Cleanup Technology

The most common technological methods of active remediation at LUFT sites are pump-and-treat, free product skimming, soil vapor extraction, bioventing, and over-excavation. Pump-and-treat involves removing contaminated groundwater from the plume, removing FHCs using activated carbon or other methods, and returning the treated water to ground. Free product skimming involves installing a well in the source area. Due to differential densities, any free product present floats on the groundwater in the well column space where it can be skimmed. Soil vapor extraction involves the removal of soil vapor from vadose zone wells using a vacuum extraction system. As a vacuum is applied, volatile FHCs are drawn from free product or dissolved phase into the vapor phase and removed. Steam injection into the ground in the plume area has recently been used with success to increase significantly the volatilization rate. Bioventing involves increasing oxygen levels and microbial action in the plume through the installation of soil vent pipes. Over-excavation is the process of completely removing contaminated soils in the source area and removing the FHCs though, for example, soil washing or incineration. The excavation is then filled with treated soils or clean fill.

Pump-and-treat remediation is the typical alternative used at LUFT sites. This technology, however, has been found to be no more effective than bioremediation once the active source has been removed (Rice et al., 1995; Mace et al., 1997). FHCs sorbed to soil particles are difficult to remove and remain even after contaminated groundwater has been removed (Isherwood et al., 1993). To remove FHCs by flushing can require hundreds of volumes of water. Even if groundwater FHC concentrations are reduced, FHCs desorb slowly (Karickhoff et al., 1979). For these reasons, pump-and-treat is not recognized as an effective method of remediating FHC contamination to MCL goals (U.S. Environmental Protection Agency, 1994).

Rice et al. (1995) evaluated 224 LUFT sites that had increasing or decreasing plume concentrations or high FHC concentrations that were stable over time. For these sites, tests were conducted to determine if active remediation efforts or depth to groundwater could predict whether a plume exhibited increasing, stable, or decreasing concentration trends. The results indicated that the use of either pump-and-treat or over-excavation increased the probability, from 0.72 to 0.77, of having a negative trend, and a combination of technologies increased the probability to 0.83. None of these estimates, however, was statistically significant.

A significant conclusion of the LUFT team was that combinations of treatment technologies performed better than a single, focused technology because of a tendency of all technologies to reach limits of effectiveness. From an optimal control standpoint, this finding implies that the cleanup function may have a kink, or a series of kinks, depending on how many and when technologies were employed, at which the cleanup function may not be differentiable. Differentiability is a key to characterizing the optimal interior solution in the dynamic model proposed by Caputo and Wilen. The use of different combinations of multiple technologies over time would imply that this model may not yield a unique solution.

It should also be noted that the time necessary to achieve MCLs using active remediation methods, even considering the beneficial effect of natural processes, is usually far greater than the reasonable planning horizons considered by regulators. For example, the Lahontan RWQCB considers 50 years to be a reasonable planning horizon, but at George Air Force Base the cleanup of Operable Unit #2 would take significantly longer than 50 years (Rice et al., 1998). For this reason, the Lahontan RWQCB has an additional goal of reducing the uncertainty regarding the risk to future users of the site. The length of the societal “damages” in this instance implies that the risk of adverse effect is spread across generations. As noted by Cropper and Sussman (1990), the valuation of damages to a future generation depends on that generation’s discount rate, which can only be determined by that generation. Because Caputo and Wilen’s model requires a comparison of discounted damages to discounted costs, the lack of knowledge regarding a future generation’s discount rates limits the model’s applicability.

V. Nature of the Social Damage Function

Social damages that result from a release of FHCs from an LUFT can, in general, take one or more of three forms. First, an exposure of a human or ecological receptor to FHCs could result in an increased risk of physiological damage to, or impairment of, the receptor. Second, because there is the potential for exposure of humans to FHCs present in an area, the site and surrounding areas may be limited to uses that have lower economic value than their unrestricted use. Third, subsurface soils and groundwater have been considered receptors that are damaged by exposure in and of themselves. Each of these will be discussed in turn.

V.1 Human and Ecological Health Risk

FHCs contain a large number of individual compounds; some of which are known to pose a health risk. A compound can cause acute health effects, i.e. immediate or very short-term effects, chronic effects (which are adverse health effects that develop over time due to multiple, low-level exposures), and cancer. For adverse health effects to occur, it is necessary for the chemicals present in the FHCs to come into direct contact with receptors, usually with specific organs within the body before damage or impairment will occur. The pathways for chemical exposure to internal organs usually considered in risk assessments are ingestion of contaminated soils or groundwater, inhalation, and dermal exposure. Dermal exposure is not usually found to contribute significant amounts of chemicals to the total exposure. Inhalation of volatile compounds and ingestion of contaminated groundwater are the primary pathways for human health exposure.

Determining total exposure to a human or ecological receptor requires assumptions about the behavior of receptors, particularly behavior that would lead an individual to be present in an area where chemicals are present (see, for example, Katsumata and Kastenberg, 1997). For humans, this involves determination of site uses which, in turn, imply the presence of individuals at specified points during defined intervals. For animals, this involves some model of foraging behavior and a determination of whether appropriate habitat is present in the affected area.

Because exposure occurs over time, it is important to estimate the way in which the spatial extent of plumes and plume concentrations vary over time. The exposure-point concentration is a function of the spatial extent of the hydrocarbon plume, which is determined by groundwater velocity, the hydraulic conductivity of the soils, air and water dispersion coefficients, the mean biodegradation rate, the conditions controlling the dissolution of mass into the plume, the retardation, the porosity, the aquifer vertical thickness and other parameters. In the best of circumstances, these parameters are hard to measure, and most sites lack time-series data necessary to estimate plume extent and movement.

The health risk associated with a FHC release depends on the exposure of an individual over time. The compounds present in FHCs include those that could cause acute or chronic health effects, or cancer. Each compound has its own unique solubility and vapor pressure, which implies that compounds move through soils to an exposure point at different rates. The determination of the exposure-point concentrations of the variety of compounds in FHCs during each period that the individual is assumed to be present is clearly very complicated. For this reason, the usual approach is to make a variety of worst-case assumptions regarding the fate and transport of chemicals and the behavioral patterns of the potentially exposed humans and ecological receptors.

As a hypothetical FHC plume spreads or land-use patterns change, the number of individuals in the affected area of the plume may also change in a discrete manner. Acute effects that result from short-term exposures to high concentrations of chemicals, and cancer effects that could result from a single exposure may also occur in discrete intervals as the numbers of individuals exposed changes. For this reason, the social-damage function may exhibit a series of discrete jumps as the FHC plume spreads and land uses change over time. From a practical standpoint, it is unlikely that sufficient data are available to determine health effects quantitatively over time. From the standpoint of the Caputo and Wilen (1995) model, there is no reason to believe that the social-damage function is continuously differentiable.

It should also be noted that the first “unit” of FHCs released would not cause any social damages because a single “unit” would not be large enough to reach and contaminate groundwater or reach a human or ecological receptor. However, whether or not the first unit of waste created any marginal damage is critical in the Caputo and Wilen model as to whether the optimal solution allowed a partial cleanup or whether a complete cleanup is required.

V.2 Land- and Groundwater-use Limitations

California’s RWQCBs have used several tools to limit the potential health risk associated with FHC releases, including the use of well construction standards to prevent the installation of wells in contaminated aquifers. At wells near LUFT sites, groundwater quality is also monitored for the presence of FHCs. A third tool is the use of deed restrictions to limit future human activity at a contaminated site. Of course, the primary tool used is to require responsible parties to remove the FHC source and conduct active remediation to MCLs.

As discussed previously, the human health risk associated with a FHC release is a function of exposure, which, in turn, is a function of the duration of human presence at the exposure point. The age of the humans present and the duration of that presence at any exposure point can be subject to regulatory restrictions, such as deed restrictions on allowed property usage. (For example, if a site were zoned for industrial use, children would usually not be present for significant time periods.) RWQCBs have used deed restrictions to limit future human exposure at contaminated sites. Because residential use is considered to be the highest and best use in some areas, deed restrictions may result in lower economic rents to the property than would accrue to a site if unrestricted use were allowed[1].

In addition to land-use limitations, the RWQCBs monitor groundwater usage in areas surrounding LUFT sites. Well construction standards are used to prevent installation of drinking water supply wells in aquifers impacted by FHC releases. These standards have been shown to be very effective in eliminating a significant pathway for human exposure. The implementation of well construction standards effectively restricts usage of impacted aquifers.

Rice et al. (1995) found that the cost of remediating impacted groundwater resources was significantly higher that developing new sources. The average cost of remediating groundwater was estimated to be $637,000 per acre-foot. The average cost of developing new water supplies was between $700 to $900 per acre-foot. These are state averages, and site-by-site costs may vary significantly.

No estimates of lost rents due to deed restrictions were found. Lost rents are potentially significant costs to society that should be included in the model proposed by Caputo and Wilen (1995). If these costs are not accounted for, the cleanup time estimated using the model could be significantly longer than the true optimal cleanup time.

V.3 Impacts to Aquifers

In the past, the California SWRCB and the RWQCBs have considered water resources themselves to be ecological “receptors” as opposed to being only pathways for the transport of chemicals in the environment. Any contamination of groundwater, therefore, was considered *a priori* to be unacceptable. Consideration of aquifers in this light became a further regulatory driver of remediation to MCLs or background levels. In theory, contingent valuation methods could be used to determine the intrinsic value of an uncontaminated aquifer. No attempt to do so was found. However, such a valuation would be necessary to assess fully the discounted costs to society resulting from aquifer contamination. The lack of data in this area and the well-known problems associated contingent valuation of such an esoteric resource would appear to limit the use of the Caputo and Wilen model to provide an accurate forecast of the optimal cleanup time.

VI. Rate of Decay

A key assumption in evaluating the optimal cleanup of waste in the environment is its natural rate of decay. Several authors, including, for example, Caputo and Wilen (1995), define the rate of pollution decay as a linear (or monotonically increasing) function of the pollution stock. This assumption, however, has been criticized on the basis of an assumed maximum environmental assimilation capacity. An alternative formulation by Tahvonen and Withagen (1996) describes an "inverted U-shaped" decay function which represents a reduction in the decay rate at sufficiently high levels of pollution. If the decay function has an inverted U-shape, several problems can arise because the function is neither concave nor convex (Tahvonen and Withagen, 1996). Odom (1971) also notes that the function, at critical points, may not be differentiable. The optimality candidates may give a local minimum only and not a global solution (Tahvonen and Withagen, 1996). For these reasons, the shape of the rate of decay function is important in determining the optimal cleanup of hazardous waste.

Microbial populations that use FHCs as a food source are ubiquitous in soils. As FHCs at a LUFT-site pass through soils and dissolve in oxygen-rich groundwater, these microbial populations become active in degrading FHCs, converting them to organic acid intermediates and finally to carbon dioxide and water. Oxygen is more available around the margins of the plume than in the interior, and aerobic microbial degradation proceeds faster in this area than in the anaerobic core of the plume. U.S. Air Force studies indicate that, in many geochemical environments, there is an excess potential microbial biodegradation capacity (Rice et al., 1995; Mace et al., 1997). Because of this excess capacity, a FHC plume mass and spatial extent may be expected to remain stable, even in the presence of an active FHC source. This hypothesis has been verified in field measurements in which plume length stability is often reached at a distance from the source much less than what would be calculated using groundwater models (Rice et al., 1995; Mace et al., 1997). In the absence of continued FHC releases, biodegradation would result in plume collapse and, ultimately, in complete conversion of FHCs to nonhazardous compounds.

The dynamics of the biodegradation process have several implications for the shape of the rate of decay function. Because most major LUFT sites in California have been identified and the FHC source removed, the great majority of sites have inactive sources. However, as discussed previously, gravity, hydraulic head, vapor diffusion, and groundwater movement cause a mass of FHCs in soils to spread over time in a plume, even without an active source.

Assuming that a LUFT is installed above the water table, the initial release of FHCs would be to unsaturated soils. The rate of decay immediately following a release is expected to be zero for two reasons. First, at the initial release point, the concentrations of FHCs are high enough to be toxic to microorganisms, even to microbes that use FHCs as a food source. As the FHCs spread through soils, they diffuse and combine with available soil moisture; and after a period of time, concentrations are reduced to non-toxic levels. Second, laboratory studies have found that there is a time delay between the exposure of microbes in the saturated zone to FHCs and the onset of microbial degradation (Rice et al., 1995). Although microbial activity in the unsaturated zone is not as well understood as microbial activity in the saturated zone, a similar stimulus/response delay would also be expected. Due to the high toxicity of concentrated FHCs upon initial release and the delay in microbial response, no appreciable decay would be expected to occur for period of time following the initial release.

Unless the water table is very deep, the FHCs will reach groundwater and spread in a plume. Early in the life of the plume, the anaerobic core of the plume is larger in its surface area than the aerobic margins where FHCs are degraded faster. As the plume spreads, the aerobic margin increases, increasing the instantaneous rate of decay of the overall plume. This implies that, as the plume spreads, the mass of FHCs degraded through microbial action will increase, again assuming that the source is inactive.

At some point, the margins of the plume will have increased to a point at which the aerobic surface area is relatively large and the decay rate reaches a maximum. Past this point, microbial degradation will continue, causing a slow plume collapse. More soluble compounds are metabolized quicker, with longer times required for dense or insoluble compounds, or compounds sorbed onto particles. For this reason, the FHC decay rate would be expected to decline with the change in the decay rate slowing over time as the remaining FHCs become harder to degrade or are limited to those with more difficult access. Due to these factors, the process of degradation at this point is very hard to model; and the time scale required for complete remediation cannot be predicted with high confidence.

Because the decay rate depends on the spatial extent of the plume and on microbial action, both of which change over time, the decay rate could also be represented as a function of time. High initial stock levels would occur early in the life of the plume; the decay rate would be low during this interval due to toxicity and the delay in microbial response. As the remaining stock spreads over time and the aerobic margin increases, decay begins and increases. Therefore, at a stock levels close to the initial stock level, decay and stock levels are negatively correlated. Later in the life of the plume, the rate of decay increases further and reaches a maximum, followed by a decline as the mass of FHCs is reduced. Therefore, as the stock level declines during this period, the decay function goes from being negatively correlated with stock levels to being positively correlated. As the mass is further reduced, the velocity of the rate reduction is reduced as microbial degradation becomes more difficult, with the rate of decay asymptotically approaching zero. For these reasons, the decay rate is neither linear, nor a monotonically increasing, function of the pollution stock level. The inverted U-shaped decay function discussed by Tahvonen and Withagen (1996) is relevant in describing the decay of FHCs in soils and groundwater.

Based on this discussion, the dependence of the convexity of the decay function on the life stage of the plume is important in evaluating the optimal cleanup of FHCs. The previous discussion aside, however, it is important to remember that because most FHC releases in California occurred in the past, underground plumes have usually reached their maximum spatial extent and stabilized; and microbial action has already begun. Therefore, at the beginning of the planning horizon in the optimal control problem, an evaluation should be made regarding the life stage of the plume. If field data show that a plume has stabilized or is collapsing, and if microbial activity is declining, it can be assumed that the plume is in its later life stages; and the decay function would be strictly convex over the planning horizon. In this case, the shape of the decay curve at higher initial levels of the stock of waste would have no bearing on whether the optimality candidates were local or global minimums.

Rice et al. (1995) developed a hypothetical model of a plume life cycle using 221 well-characterized sites. This life cycle, in terms of average plume concentration over time, is reproduced in the attached figure. During Phase I, the source is active, mass is being contributed to the plume, and average plume concentration grows. About 8% of the plumes appeared to be in this life phase (Rice et al., 1995). During Phase II, a zone of passive bioremediation is established in which mass is removed from the plume and the plume stops growing. The plume is relatively stable during this period as the mass contributed by the active source is matched by the mass removed by microbial action, sorption to soil particles, and volatilization. About 16% of the plumes appeared to be in Phase II of the life cycle (Rice et al., 1995). In Phase III, the source is depleted or removed. The plume length decreases slowly while mass is depleted rapidly. About 59% of the plumes evaluated by Rice et al. (1995) appeared to be in this life phase. In Phase IV, the plume has relatively low residual mass and temporal changes in mass or length are insignificant. Plumes in this phase are considered to be “exhausted.” About 17% of the plumes appeared to be in this life phase (Rice et al., 1995).

Average concentrations of plumes in life phases III and IV are declining exponentially (Rice et al., 1995). Actual values of the decline in concentrations vary widely with a mean of about 0.001 ppb per day. Because concentration trends are log-linear, the inverse of these numbers is the amount of time required for average concentrations to decrease tenfold. The range is from 1.5 to 7 years with a median time of 3.2 years. A recent review of 200 LUFT cases in Napa County, California, found that once the contaminant source was removed, FHCs in groundwater appeared to degrade naturally, in some case at a rate of up to 50-60% per year.

Because 76% of the plumes evaluated by Rice et al. (1995) appear to be in Phase III or Phase IV, the assumption of a constant exponential rate of decay may also hold for a significant portion of the 21,000 LUFT sites in California. At these sites, the assumption of a rate of decay being an increasing function of the pollution stock appears to be valid; and one of the necessary requirements of the model of optimal cleanup developed by Caputo and Wilen (1995) would hold.

Unfortunately, however, the application of active remediation further complicates the use of the Caputo and Wilen model in that the rate of decay will vary depending upon the timing and the rate of remediation efforts. Many, if not all, plumes have areas, or lenses, of highly concentrated FHCs. Over time, the plumes tend to reach a dynamic equilibrium in which groundwater movement, biodegradation and other factors “pull” FHCs out of highly concentrated areas at a fairly constant rate. Once active remediation efforts, such as pump-and-treat begin, the equilibrium is disturbed; and the rate at which FHCs dissolve into the plume increases. The pump-and-treat operations also pull back FHCs from other areas of the plume where biodegradation is taking place. The decay rate, therefore, is dependent upon the type and the level of active remediation efforts employed. This interdependence of decay rate and remediation effort is not accounted for in the model proposed by Caputo and Wilen (1995).

VII. Optimal Control Problem

Based on the previous discussion, there are few California LUFT sites where it would be possible, even in theory, to formulate a solvable optimal control problem. On the one hand, over half of the plumes may be experiencing exponential rates of decay. If the plume is stable or collapsing, there may be no significant current or future risk to human health or ecological receptors. However, because more than one cleanup technology would probably be required in most instances, the cleanup function may not be differentiable throughout the remediation period. The only real social damage is the loss of economic value caused by land- or water-use limitations during the remediation and decay of the plume. As soon as MCLs are met, the social damages abruptly end. Therefore, although the rate of decay may meet the assumptions at many LUFT sites in California, the non-differentiability of the social damage function and the cleanup function, and the interdependence of the rate of decay function and remediation efforts may preclude using the Caputo and Wilen model to determine an interior solution.

An alternate way of viewing the regulator's problem at many LUFT sites is to compare the cost of imposing deed restrictions at contaminated sites to the projected benefit of reduced risk to future users. Even though plumes do not pose human health or ecological risk at most LUFT sites, California policy allows cessation of cleanup only if institutional measures exist to limit the risk to future site users. Because these measures limit site uses until groundwater meets MCLs, society may lose rents that would have accrued to the property under its unrestricted use. Under deed restrictions, the present value of lost rents during the cleanup period can be considered the cost of reducing the risk to future receptors. Knowledge of the full cost of risk reduction would be important in determining whether or not to impose deed restrictions.

Also using this approach, the cost of active remediation efforts could be compared with the benefits of shortening the time during which site uses are limited. As remediation efforts are applied, the total time to reach MCLs is reduced along with the total lost rents. If remediation efforts are very effective, and if the difference in site rents between restricted and unrestricted use is significant, active steps may be justified from an efficiency standpoint.

As discussed previously, adding "effort" in this sense generally means adding another treatment technology over a specified time period. The addition of another technology would shorten the anticipated cleanup time and reduce the lost rents by a discrete amount. Because the number of treatment options are limited, each combination could be evaluated.

VIII. Conclusion

In California, LUFT legislation was conceived because of concern that "time bomb plumes" would ultimately impact a significant portion of the state's ground and surface water resources. However, it has been found that FHC plumes are stable at relatively short distances from the source in areas of shallow groundwater. In urban areas, these shallow aquifers are not even recommended for use because they are subject to contamination from sewers, storm drains, septic fields and a variety of other sources. After the FHC source has been removed, risk to human health or the environment is insignificant in most cases. For this reason, cleanup to MCLs will not significantly reduce the social damages associated with current or near-term human health or ecological risk. Based on these findings, California would be able to save significant resources that had been allocated for LUFT-site cleanup.

Non-convexities in the rate of decay function and non-differentiability in the cleanup and social damage functions appear to limit the usefulness of models, such as Caputo and Wilen's (1995), that attempt to characterize the optimal cleanup path using marginal analyses. Furthermore, the effect of active remediation efforts on the natural rate of decay in stable plumes is not taken into account in their model.

The imposition of deed restrictions prior to a demonstration of cleanup to MCLs is an additional conservative measure imposed by the California RWQCBs to reduce the uncertainty associated with health risks to future users. These measures impose costs on society in the form of lost rents that have not been considered by regulators. By estimating the differential rents during the time to cleanup, regulators would be able to compare the costs of imposing deed restrictions with the values that society imparts to protection of future users.

Both land and water sources are unique in that the value of each is highly dependent upon location. For cost-benefit analysis to be effective, site-specific estimates of property and groundwater values need to be established. Future research may focus on deriving site-specific estimates of restricted and unrestricted land and water usage.

Endnote

1. The highest and best use of property depends on its location. Deed restrictions that do not restrict a use that is best for site's location will not result in lost rents. For example, deeds may restrict sites from being used for residences, schools, or day care centers. If the site is on the corner of a well-traveled intersection, commercial rents would probably exceed rents gained from these other uses.

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